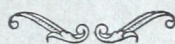


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STEEL *for* STRENGTH *and* SECURITY

By GEORGE F. SWAIN, LL. D.

*Past President Am. Soc. C. E.; Honorary Member, A. I. S. C.;
M. Am. Soc. M. E.; M. A. R. E. A.; M. A. S. T. M.; Professor
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1928

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The principal materials used in structures are wood, stone, burnt clay products, concrete and reinforced concrete, and steel (including iron and alloys). Each of these is valuable, and appropriate under certain conditions. Good engineering requires the use of each where it is most suitable, everything considered.

It is the purpose of this paper to compare these materials, but mainly to compare reinforced concrete with steel and iron, and to give the reasons for my conviction that reinforced concrete has been and is being very much over-advertised, over-praised, and over-boomed, with the result that it has been and is being used in many cases where steel is decidedly preferable.

What are the desirable characteristics of a structural material? It depends to a large extent upon the purpose and use, and the kind of stress to which it is to be exposed, but the following characteristics will probably be admitted to be generally desirable, not stated in the order of their importance:

1. Economy
2. Durability
3. Strength

Economy is desirable if there is equal durability and strength, and economy must take account of cost of maintenance and ultimate replacement.

Durability is always desirable.

Strength must be sufficient for the purpose.

Under the head of strength, or closely related to it, are some other desirable qualities, namely:

4. Elasticity, or the property of not taking a permanent set unless the stress exceeds a well defined limit, the larger the better.

5. Resilience, or the power of requiring a large amount of work to be done upon it before fracture, which is "total resilience," or before

taking a permanent set, which is "elastic resilience."

6. Toughness, which is about the same as total resilience. It implies the absence of brittleness, the presence of ductility, elasticity, great resistance to blows, and high strength.

7. I have a strong conviction that a large tensile strength is very desirable, even in a material which is to be exposed only to compression. There are several reasons for this. In the first place, if a material fractures, it must be by tearing apart of the particles, and must involve tension. A ductile material like steel may lose its usefulness in compression by bulging; a fibrous material like wood may fail by crumpling of the fibres: but a *rupture* can only occur by a tearing apart of particles. Even a shearing failure must involve tension. In the second place, a prismatic compression piece with stress uniformly distributed over the ends will expand laterally. On any longitudinal section there can be no *resultant* normal stress unless there is a tangential force on the ends, but even if there is no resultant normal stress there may be, and probably are, tensile and compressive forces which balance. Any thin, longitudinal strip, if alone, would bend laterally; hence in the column it must *tend* to bend laterally, and there may well be tensile forces near the center of the length, and balancing compression forces near the ends.

Also, in a granular material in compression, a circumferential tension will greatly reduce the tendency to shear on diagonal planes.

Therefore, I think high tensile strength desirable even in a column. I think that, if other things are equal, a material with a high tensile strength will have a high compressive and shearing strength.

8. Another desirable property is that of usability at all times and seasons, independent of weather.

9. Still another desirable property is constancy, that is, not being subject to change,

*Address before the Fourth Annual Convention, American Institute of Steel Construction, Inc., White Sulphur Springs, W. Va., October, 1926. Executive Offices, 285 Madison Ave., N. Y.; Engineering Dept., 1052 Leader Bldg., Cleveland, O.

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1090-0-1790 721

physical or chemical, after being put into the structure, especially not being subject to unknown changes.

10. Another is absence of initial stresses, especially unknown and varying initial stresses, and those which cannot be removed or avoided.

11. Finally, one of the most necessary qualities is *reliability* or freedom from risk if proper care is taken.

There are other desirable qualities, but I think the above list comprises the principal ones.

Wood is an excellent building material. If not exposed to the weather, and with proper circulation of air about it, it may last for centuries; and even if exposed to the weather, if kept well painted, it is very durable. It has large strength except in shear along the grain, and its tensile strength is particularly large. It is sufficiently elastic, resilient and tough. It will always be largely used, but is becoming more costly owing to the exhaustion of our forests, and on this account is being replaced by clay products, mortar and concrete, and by steel.

Stone has its well-defined uses; and, if sound, is strong and durable.

Burnt clay products also have well-defined uses, and are strong, durable, and not subject to attack by corrosion.

How does reinforced concrete compare with steel? To answer this question is the main object of this paper. First, let us consider certain qualities of steel and of reinforced concrete.

Steel is a finished product, the result of years of experience, experiment and study. It comes to the work in its finished form, the product of years of experience by manufacturers, metallurgists, engineers, expert superintendents and foremen, and experienced workmen. It has, in higher degree than any other material, all the desirable qualities that have been named. It is exceedingly strong, durable if properly taken care of, elastic, resilient, tough, with great tensile strength, usable at all times, unchanging, and reliable. It may have initial stresses, but they may be reduced or removed by annealing, so that practically they are not dangerous. It may be tested before being used. Each heat may be tested; or each piece, if desired. It may, of course, have defects, as every material may,

such as seams, segregation, piping; but there are ways of preventing these and of finding out whether they exist. Magnetic and electrical tests are being used, as well as physical tests. The chemical composition and the physical properties can be accurately controlled.

In a long structural experience, I have never met with a case of failure of a steel structure on account of poor material, though I know of one standpipe which failed from this cause; but the poor material could have been detected and rejected. Steel structures have failed, but almost always on account of poor design or overloading. If a steel structure fails, except from an accident such as a derailed train, or from an act of God or public enemies, it is almost always true that the failure could have been predicted by a competent engineer after an inspection, and it almost always gives warning beforehand. This is not true of reinforced concrete. This holds good even for the first Quebec bridge, for which, immediately after the failure, as soon as I received sufficient data, I made a computation which showed that it should have failed just when it did, and with no knowledge of steel then that I did not have before the failure.

Steel does not change after it is put into a structure. It does not crystallize under repeated loads. It is subject, as all materials are, to expansion and contraction due to changes of temperature, but, if statically determined, these need not cause stresses; and, if not, they may be computed. It is not porous.

As compared with these qualities of steel, the first peculiarity of concrete to be noted is that it is not a finished product. It is made *on the job*. The engineer must not only design the structure, but he must *design the material*. The constituents, stone, sand, cement, and water, are each subject to defects that must be guarded against, and they are extremely variable. The stone and sand must be graded properly in size, and mixed in proper proportions with the cement and water; and this must be done, not in the laboratory or factory, but on the job, with all the necessary uncertainties, and often with very unskilled labor. The material is not finished until it is in the structure, and then it cannot be tested or rejected. Even then it is not exactly finished, because it changes

after it is in the structure. Indeed, the main part of its manufacture, which gives it strength, takes place after it is in place, and beyond the possibility of rejection.

At first, concrete was proportioned quite arbitrarily, and it was thought that the only ingredient to be carefully controlled was the cement. Then it was recognized that the sand and stone were equally important. Finally it has come to be generally believed that water is the most important of all, and we are told that the strength depends almost entirely upon the ratio of water to cement, which should be as small as possible so long as workable mixtures are obtained; and that "the grading of the aggregate which produces the strongest concrete is not that giving the maximum density (lowest voids)." The workability for the purpose in view will dictate the minimum quantity of water. The workability will depend not only upon the quantity of water, but upon the grading, quantity, and maximum size of the aggregate and the shape and smoothness of the individual grains. The moisture originally in the aggregate must be allowed for. One pint more water than necessary to produce a plastic concrete is said to reduce the strength as much as if 2 or 3 lbs. of cement were omitted from a one-bag batch. These are the results arrived at by Professor Abrams, at the Lewis Institute, for the Portland Cement Association, and they have been widely adopted and used. On the other hand, some believe that the surface area of the aggregate is the important factor. I am conservative enough to cling to the idea that there should be cement enough to fill the voids of the sand when hydrated, and to coat the surfaces of the aggregate, and enough mortar to fill the voids of the coarse aggregate with a small excess. If there is anything in this, the surface area should be at least an element to be considered, but Professor Abrams does not think so. It seems to me that the best discussion of the matter is that of Professors Talbot and Richart, in Bulletin 137 of the University of Illinois, and this is not altogether in agreement with Professor Abrams, though the importance of the water-cement ratio and the desirability of limiting the quantity of water are acknowledged. The matter does not seem to me to be so settled as many believe it is. It seems to me

also that too much attention has been given to strength, and not enough to *imperviousness*, which is *more important* from the point of view of durability.

But another most important characteristic of concrete is that it changes *after it is placed beyond recall in the structure*. In this respect it differs radically from all other structural materials. The real manufacture of the material begins then, when it begins to set and harden. The phenomena of setting and hardening are not fully understood. It seems to be partly a crystallization, but mainly the hardening of a colloidal mass composed of cement particles which absorb water and swell, the water gradually penetrating into the particles. Some of the water absorbed is held permanently, but a large part is held loosely and is given up when the concrete is dried out, causing a shrinkage of the concrete. If the concrete is exposed constantly to water, it will expand as the colloidal mass absorbs water. When and if the voids at the surface become filled, water will be absorbed very slowly, and the surface becomes practically impervious. This may happen at the face of a concrete dam exposed to water, which may become practically water-tight in a short time. But if the concrete is dried out, the water will be given up and the concrete will be porous. If again wetted, water will be again absorbed, more quickly than before, and in greater quantity than before, as it penetrates farther than before into the cement particles. At each successive drying out the concrete will shrink, and when wet again it will expand, each time a little more than before. It is not known how much water is required for complete hydration, nor how long it will take to produce it. Professor White found concrete twenty years old still susceptible to alternate expansion and shrinkage on successive wetting and drying. It is considered desirable to have always an excess of cement.

All concrete, unless waterproofed, is more or less porous, and will swell and shrink when wetted and dried, and with varying moisture in the atmosphere.¹ Further, a large part

1. See Bulletin No. 3, University of Minnesota, Studies in Engineering, by Franklin R. McMillan, on Shrinkage and Time Effects in Reinforced Concrete, where it is shown that changes in moisture of the air at different seasons produce these expansions and contractions.

of the cement in concrete is soluble in water, and can be dissolved out or can form other compounds with acids in the water.

Consider the situation for a moment. Concrete is a material made on the job, dependent upon the quality of stone, sand, cement, and water, the proportions, the care in mixing and placing, and much influenced by small variations in the quantity of water used. It sets after being placed beyond recall. Its ultimate condition depends much upon the curing, or treatment during setting, and the amount of water given it. It expands and contracts subsequently as it is wetted and dried. Is it not obvious that there *must* be considerable uncertainty in the resulting product? Modern methods of field control have made it easier to secure uniformity and good quality, but great lack of uniformity still exists. If a pint of water in a batch makes so much difference, how can we expect uniformity with ordinary workmen, varying weather and varying moisture in the materials? What would be thought of steel if the ingredients, iron and carbon, or ferrite, cementite, and amorphous material had to be selected from widely varying materials, mixed in the field, put into the structure when molten, and allowed to harden there? How much better and more reliable than concrete is a material like steel, which comes to us a finished product that can be tested, which suffers no change of constitution when put in the structure, which is not porous and cannot have its constituents washed out, and is only subject to surface oxidation, which can be prevented!

The strength of concrete varies with the temperature and with the degree of saturation. According to Professor A. B. McDaniel (Bulletin 81, University of Illinois) the compressive strength of 1—2—4 concrete at 28 days varied from about 1520 lb. per square inch when kept at 90°F. to less than 500 lbs. when kept at 15°F. He says that concrete one week old maintained at a temperature of 60° to 70° will have practically double the strength of the same material if kept at 32° to 40°. Professor Van Ornum, in Trans. Am. Soc. C. E., Volume 77, found that 1—2—4 concrete six weeks old, kept two days in the molds and then immersed in water at different times showed very different strength according to the time in water. If only

two days in water, the strength was 63 per cent of the strength if kept all the time in air, and if kept 40 days in water it was 150 per cent of the strength if kept all the time in air.

But this is not all. Setting in water, reinforced concrete expands, causing tension in the steel and compression in the concrete. Setting in air, it contracts, causing compression in the steel and tension in the concrete. Professor White says that "these volume changes, which seem due to a fundamental property of Portland cement, are the most potent causes of the destruction of concrete exposed to the weather. If concrete is to be kept constant in volume, its moisture content must be held relatively constant," and this cannot be done unless it is waterproofed and all water prevented from entering, and in this case complete hydration will probably be prevented.

The expansion of 1—2—4 concrete in water may amount to 0.01 per cent in 120 days, and the contraction in air to 0.05 per cent or more. This means that a bar 100 feet long may contract 0.6 inch. If this bar is reinforced, the contraction will be less because the steel will resist it. If the modulus of elasticity of concrete is 2,000,000, and the percentage of reinforcement 0.5, the compression in the steel, if all parts of the length contract alike, would be about 14,000 lbs. per square inch, and the average tension in the concrete about 75 lbs. per square inch. If the modulus of elasticity of the concrete is 3,500,000, as it may be when fully hardened, the stresses will be larger. The tension in the concrete will not be uniform over the whole section, but will be greatest at the rod, where it will much exceed the average, while at the edges it will be less.¹ Also, in a bar shrinking, the maximum stresses will be at the center of the length and the maximum bond stress at the ends, and the maximum stress may be 50 per cent greater than stated above. In a 10 x 10 inch bar 10 feet long with one ¾ inch rod, the bond stress may be 130 lbs. due to shrinkage. In Bulletin 126 of the University of Illinois, measurements of stress are reported showing in a bar of 1—2—4 concrete two feet long reinforced by bars anchored with lugs at the ends

1. See "Shrinkage and Temperature Changes in Reinforced Concrete," by E. H. Harder, Engineering News-Record, April 12, 1923.

18,000 lbs. per square inch in the steel with 0.55 per cent of steel, and 15,500 lbs. per square inch with 1.23 per cent of steel; and 250 lbs. per square inch tension in the concrete with 2.18 per cent of steel. There is no doubt of the seriousness of these stresses. In columns, the shrinkage stresses may exceed those allowed in the design, while in beams the tension reinforcement will be relieved but the concrete tension increased. *These stresses have been generally entirely ignored because they were not known. The matter is uncertain and depends on many factors, but we now know enough to be sure that shrinkage stresses are serious, that they are sure to exist in all reinforced concrete drying in air, and, more serious still, that they change or alternate as the concrete is wetted and dried.*

Turning now to the usual methods of computing reinforced concrete structures, the situation is also uncertain and unsatisfactory. Consider first reinforced concrete in flexure. By the accepted theory, the bending moment at any section is resisted by the compression in the concrete above the neutral axis, and the tension in the steel below it. There is surely tension in the concrete below the neutral axis, until the concrete breaks, but this tension is neglected, and assumed not to exist. In other words, the concrete is assumed to break. Yet shear and bond stress are computed on the assumption that the stress in the steel varies with the moment; in other words, that there is no slipping of the rods, but a perfect bond, which means tension in the concrete around the rods, which was assumed not to exist in computing the rods. That is to say, the accepted theory assumes in one place that there is no tension and in another place that there is tension. As a matter of fact, nobody knows how a reinforced concrete beam acts. It probably acts partly as a beam, partly as an arch, partly (if rods are bent up at the ends) as a catenary or suspension system, and nobody knows to what extent in each way. And I have always wondered just what bond there is in a reinforced concrete beam after it has been in use for some months or years, and exposed to a series of alternate wettings and dryings, with accompanying shrinking and swelling. In Bulletin 126 of the University of Illinois, previously referred to, it is stated that the in-

dications were that slipping of the bars took place during the shrinking. The theory for shear and bond is very uncertain. The beam is supposed by some to act as a Howe truss, though no attention is paid to the truss connections. The bond is certainly not distributed as the usual theory assumes, and the stress in the steel at a point where the moment is not a maximum may, if there is truss action, be greater than computed.¹ The bond may not act in the same direction at all points of a bar, and suddenly increases where a bar is cut off. I am forced to the conclusion that the theory of reinforced concrete is still almost wholly empirical. We know little about it except that certain beams have carried certain loads in laboratory tests.

Further, it is to be observed that before a beam can act according to the usual theory, with the rods stressed to say 16,000 lbs., the concrete must crack. *This is the only structure composed of two materials in which the accepted theory presupposes the actual rupture of one of the materials.* This certainly does not look very good.

Consider now the concrete column reinforced by longitudinal rods. The shrinkage of the concrete due to varying moisture will, as we have seen, produce initial compression in the rods, which may be large. Now these slender rods, if standing alone and subjected to the loads that they are assumed to carry, would bend laterally. They would not carry those loads. They are only prevented from bending by the surrounding concrete. But they *tend* to bend all the time, and so tend to split off the surrounding concrete unless all the rods tend to bend toward the center of the column, which cannot be assumed. Here, then, we have a compound material in which one material tends, by its own action, to make the other fail, and does make the other fail, at the ultimate load. This again, does not look very good. I am aware of the fact that in one very excellent paper on the subject of these columns, giving the result of tests, the statement is made:

"Since in practically every failure the reinforced rods buckled, it would seem at first thought that the failure was caused by a lateral

1. For an enlightening discussion of bond, see a paper by Professor T. D. Mylrea in the Journal of the Western Society of Engineers, January, 1926.

deflection of the rods, resulting in splitting of the concrete outside the reinforcement, but in the discussion of the observations it will be shown that this buckling occurred after the failure of the concrete."

This statement leaves the inference that the rods did not cause the failure of the concrete because they did not buckle till *after* the failure of the concrete. The inference is misleading. Of course the rods did not buckle as long as they were prevented from buckling. But all the time they were *tending* to cause the failure of the concrete, and probably did cause that failure. The rods tried to break the concrete. All this explains why I do not believe in the rodded column. Such a column should always, in my opinion, be hooped. Of course I know what the tests show about hooped columns. But is it not much better to depend upon a substantial steel column inside, sufficient to carry the load, merely covered with concrete for protection?

I have shown that in this compound material, in which the steel and the concrete are supposed to act harmoniously together, the steel is tending to break the concrete, and that it actually does break under the conditions assumed in the theory. Considering the effect of shrinkage, I doubt very much whether these two materials will continue to act together permanently as assumed. We must remember the structural principle that a structure will always stand if it is statically possible to do so; so if any state of equilibrium is possible, whether by the arch principle, the suspension principle, or the beam principle, the structure will take that condition, if necessary, but we do not know what it is. It is fortunate that God (or Nature) is always on the side of the erring engineer, and will hold his structure up if possible. It is fortunate for us all.

Of course not even the simplest structure, of any material, can be computed with absolute exactness. There are uncertainties in all. But the uncertainties in the theory of reinforced concrete are fundamental and far-reaching and in my opinion far greater than in any other form of construction. Add to this the uncertainties in ordinary field work, the necessity of accurate proportioning, the large effect of small differences in the quantity of water, the human na-

ture of the ordinary workman, and it seems clear that, notwithstanding the modern progress in securing accuracy, *reinforced concrete must be very variable, and is a most uncertain material.*

Let us now compare steel and reinforced concrete with reference to the desirable qualities enumerated near the beginning of this paper.

Leaving economy out of consideration for the present, steel possesses them all. It is durable when protected, strong against all kinds of stress, elastic, resilient, tough, especially strong in tension, usable at all times, not subject to change, without dangerous initial stresses if properly treated, and reliable.

It is true that there may be initial stresses in steel, due to unequal cooling and to cold bending, and that in some rare cases they have been found to be large. But they are not usual nor large, and may be minimized by careful cooling and workmanship, or removed by annealing. In all my experience, I have never known personally of any trouble caused by them. Tests of beams and columns have never indicated any effect from them, to my knowledge. But granting that such stresses may exist in structural steel, they are much more likely to exist in the reinforcing rods of reinforced concrete, which are often bent cold and mishandled. In reinforced concrete shrinking in air, also, such stresses are sure to exist and to change with wetting and drying, thus tending to destroy bond.

Even Professor Abrams, the expert of the Portland Cement Association, in his paper on Bond, in the Proceedings of the American Society for Testing Materials, 1925, part 2, p. 266, says: "The bond strengths for the 1:2/3 and neat cement mixes are lower than for the 1:1 mix. This may be due to the volume changes of the concrete during hardening *which may tend to destroy the bond.*" (Italics mine) As a matter of fact, the bond strength for neat cement was in some cases less than for the 1:4 or 1:5 mix. If this is true for the volume changes during hardening for 28 days, how much more likely it is that the bond may be destroyed by the varying volume changes which occur for years.

Concrete, as we shall see, is subject to corrosion and dissolving out of the cement; is com-

paratively weak against all kinds of stress, and especially tension; is not elastic, but takes a set at small loads; is much less resilient than steel; is therefore lacking in toughness; requires special precautions if it is to be used in cold weather; changes after it is in the structure; expands and contracts when wetted and dried, with resulting stresses which may be serious; and is much less reliable than steel.

Concrete has to some extent a flow or plasticity under stress. Professor Hatt speaks of concrete as "markedly plastic." Mr. F. R. McMillan, in the Proceedings of the American Concrete Institute, 1921, p. 157, said:

"... There are a number of published tests in which this property has been shown to be of considerable importance in the behavior of concrete structures. In a paper before this institute in 1916, A. H. Fuller and C. C. More presented the results of some investigations made during the test of a building. They showed deformations under normal stresses continuing over long periods of time. One specimen under 1150 lbs. per square inch was still changing when the test was discontinued at 280 days, the total deformations at the end of this time being $5\frac{1}{2}$ times that produced when the the load was first applied.

"Two papers by E. B. Smith on the subject of 'Flow in Concrete' have appeared in the Proceedings of this Institute. The tests reported in the first paper, 1916, had not been carried on long, as it appeared that the deformation ceased at a few weeks, but those reported in 1917 gave measurements extending over 60 days which showed a total deformation three times that produced when the load was first applied.

"A R. Lord presented a paper to the Institute in 1917 on 'Extensometer Measurements in a Reinforced-Concrete Building Extending Over a Period of One Year' which showed this same continuing deformation. Mr. Lord found the following ratios of total deformation at the periods stated to that produced when the load was first applied,

At 55 days.....2.4 to 1
At 230 days.....5.2 to 1
At 380 days.....6.9 to 1."

This is in some respects a favorable quality,

as it indicates that a concrete structure, if watched and measured, should give warning of impending failure. But it is surely most undesirable to have a continuing flow take place under comparatively small loads, or those used in the design.

Steel, if stressed beyond the elastic limit, has that limit raised, and becomes stronger; concrete has no such property, but has no proper elastic limit. Steel does not fail suddenly except by a fatigue or impact break and it gives ample warning as a rule, while concrete is very apt to fail suddenly notwithstanding its continued flow.

As compared with steel:

Yellow pine is about one-tenth as heavy and one-tenth as strong, so that weight for weight it has about the same strength; concrete is about 0.31 as heavy, and with usual working stresses about 0.044 as strong in compression as steel, so that weight for weight it has about one-seventh the strength of steel in compression, and no appreciable strength in tension. That is, strength for strength, concrete weighs about seven times as much as steel.

On this basis, then, *does it not appear that in using concrete we are loading our structures, and especially their foundations, with great loads of sand and stone which only contribute weight and not strength?*

This comparison does not appear favorable to concrete. Only conclusive proof that reinforced concrete is more permanent and more economical can justify its use. We shall see that the claim of permanence cannot be sustained, and we will briefly consider economy later.

Notwithstanding this, please understand that I have not a word to say against the use of concrete or reinforced concrete, where they are most suitable. Concrete is a valuable and indeed wonderful material, and has many legitimate uses. I have used large quantities of it and shall probably use more. I am trying in this paper to give the facts which form the basis of my opinion that reinforced concrete is being used for many purposes where steel is far superior, and that it has inherent qualities which are far from favorable.

Let us now consider the question of the permanence of reinforced concrete. The idea of

the permanence of concrete probably originated in the fact that cement hardens gradually and gains strength with time. The permanence of concrete is sometimes illustrated by referring to aqueducts, arches, and buildings built by the ancient Romans, which are now in fair or good condition. Very true. But that concrete was not made with the materials of today, but with a very special aggregate fashioned in the furnaces of nature, the volcanic ash, or puzzolana. It was not made according to the methods of today, and, most important, it is not exposed to the climatic conditions of America and northern Europe. The countries around the Mediterranean enjoy a climate particularly fitted for its preservation.

But if examples of permanence of material are sought, we may refer to the iron "laht" or pillar of Delhi, which Thurston tells about in his "Materials of Engineering" (Volume 2, page 35). This is of soft iron, estimated to be 60 feet long or more, of which 22 feet are above ground. It is 12.5 inches in diameter at the top and 16.4 inches at the bottom, and is supposed to date from about 900 B. C. It is still in good condition. Also, iron tools have been discovered in tumuli in India which are supposed to date from 1500 B. C.

The examples of permanence in structures cited above are of historical interest, but they have no bearing on the permanence of structures of modern design under modern construction methods, no matter what the material may be.

H. S. Haines, M. Am. Soc. C. E., in a discussion of a paper on "Relative Permanence of Steel and Masonry Construction" before the Am. Soc. C. E., Vol. 49, 1902, page 85 says:

"Mr. Hildenbrand has referred to iron bolts in bridges built by Caesar across the Rhine. In the Colosseum, built about A. D. 80, the courses of heavy travertine masonry, laid with knife-edge joints, without mortar, were connected by iron clamps fairly well protected from the weather. Many of these were cut out in the Middle Ages, but those which remain appear to be in good condition. The vault of the Pantheon, 140 ft. in diameter, is of concrete supposed to be strengthened with iron rods. This vault, built about A. D. 125, is, to all appearances, in excellent condition. From these

instances, it would seem that iron, used structurally in connection with stone or concrete masonry, may remain efficient for nearly two thousand years"—in Rome.

Mr. McMillan, in his paper (Bulletin No. 3, University of Minnesota) gives results of tests of a slab which, as usually computed, should, he says, carry 100 lbs. per square foot with unit stresses of 16,000 and 650 lbs. in the steel and concrete, respectively. This slab, loaded with a live load of 100 lbs. per square foot, he states, showed "that the deflection at the end of eleven months is some 1000 per cent greater than that produced by the application of the full live load as shown on the twenty-fifth day." There was a large increase in the last two months.

No material, probably, is permanent under all conditions. There are always destructive agencies that may destroy it. Steel and iron are, as we all recognize, subject to rust, which is merely surface oxidation, and which may be prevented if care is taken. There is no internal change, no dissolving out of any ingredient. Concrete is very different. Practically all concrete is porous. The cement may be dissolved out. The concrete in reinforced concrete beams is assumed to crack if subjected to the assumed loads. Freezing and thawing may disintegrate it. The effect of salt or alkali earth is very harmful. Indeed, concrete corrodes, as steel does, but in a more harmful way. Concrete will be permanent under favorable conditions. But conditions necessary for permanence seldom or never exist. A great deal of concrete work has been built. Some of it has lasted well, but a great deal has disintegrated and is going to pieces, and there have been many failures. Much depends upon proper curing, which is allowing the concrete to take up the water it needs. Concrete roads are kept flooded or covered with wet sand for a time, or covered with Cal. Professor White says:¹

"Concrete which has been properly made, and in which the colloid has been properly developed, has its interstitial spaces so filled with dense colloid when it is thoroughly soaked in water that there is no liquid water present in the pores."

1. Am. Soc. for Testing Materials, 1914, p. 239-240.

"Concrete kept constantly wet from the time it is poured will expand rather slightly and after a few years will be practically in equilibrium with its surroundings, and will not suffer further change since the pores have become filled with a dense colloid, which prevents water from acting on the unchanged cement. Such concrete will contract at low temperatures at the same rate as cast iron, but will otherwise be unaffected by freezing, and may be considered a permanent structure. It will be in compression throughout because of the development of the colloid and will therefore be strong. The slow development of the colloid of the cement in contact with water explains the decrease in leakage frequently shown by dams and reservoirs after they have been put into service."

"If the concrete has been poorly prepared, or if there has been insufficient opportunity for the cement to develop its colloid by reacting with water, then its pores when wet will contain liquid water which will expand as usual on freezing, with possible resultant disintegration."

"If concrete, and particularly rich concrete, is to remain exposed to the weather, the only way to keep it in good condition is to so place it or protect it so that it will not be subject to great fluctuations in its moisture content. The most trying conditions are those which concrete highways have to meet. As pavements are now being laid, they seem certain in many localities to prove a serious disappointment to those who are building them with the expectation that they will be permanent structures."

Professor White also says:¹

"Water is the cause of both the life and death of concrete. Reaction of the cement with water gives it strength. Continued contact with good water maintains its strength unimpaired for generations. Removal of the water of combination causes it to shrink and crack. Restoration of the water causes it to swell sometimes to more than its largest previous dimensions. Alternate expansion and contraction, due to changes in moisture, is the greatest underlying cause of the destruction of concrete structures, for the strains due to the volume changes produced by variations in the water content are usually far greater than those due

to changes of temperature. Frost is harmless unless the concrete contains liquid water. Liquid water expands on freezing. Combined water does not. Concrete when properly mixed and hardened does not contain liquid water even though it is immersed in water, for the water which enters the pores of dry concrete becomes combined with the colloid of the cement and loses its power of expansion on freezing.

"If concrete is to be permanent, its moisture content must remain relatively constant. It may be wet or it may be dry, or it may possess an intermediate amount of moisture. The absolute quantity of combined water is relatively immaterial so long as it is kept constant. The greatest trouble is found in concrete exposed to the weather. The moisture content of large masses is not uniform and the surface exposed to the weather changes much more rapidly than the interior or the surface imbedded in the ground. There is therefore frequently a differential expansion with a resulting shear stress weakening the concrete. The strength of concrete is very largely a function of the amount of combined water."

Professor White further says:¹

"Unprotected concrete exposed to the weather in localities where it is liable to become frequently soaked with water and where it may also be frozen while wet can hardly be considered a permanent material."

Mr. John R. Baylis presented a paper to the American Society of Civil Engineers, published in the Proceedings for April, 1926, on "Corrosion of Concrete," in which he said:

"Hitherto engineers have assumed that Portland cement formed compounds insoluble in water. It will be shown that this is not the case."

"Structures valued at many millions of dollars are now showing deterioration where they are exposed to water and freezing weather. In many instances the deterioration has progressed to a point where it is jeopardizing the structures, and millions of dollars will have to be spent on repairs and replacements within the next decade to keep them in serviceable condition. This should make the problem of concrete corrosion of great interest. Engineers have

1. "The Fundamental Cause of the Disintegration of Concrete," Concrete, 1925, p. 161.

1. "Volume Changes in Concrete." International Engineering Congress, 1915.

been too ready to place all the blame for disintegration on poor construction, and have not fully realized that concrete has its limitations. It is the purpose of this paper to point out a few causes for disintegration when good materials have been used. In some instances the causes are of such a complex nature that it will require years of patient research to fully explain them, but in most instances there is a similarity suggesting a common cause. It is hoped that these few fundamental facts that have been established will be a start in the solution of this important problem."

"Corrosion as used in the paper is distinguished from disintegration in that it is a weakening of the concrete by the dissolving of certain compounds from the cement. Disintegration of weak concrete may be caused by freezing when there may have been no dissolving or changing of the cement compounds."

"... More than 90 per cent of the total calcium in concrete will be dissolved by water slightly corrosive to calcium carbonate. The compounds remaining are usually soft and of a gelatinous nature."

"When good materials have been used and properly mixed, the chief factor in determining whether the concrete will withstand the weathering agents is its porosity. Air-bubbles, which under ordinary practice are not excessive, have little effect. It is the spacing between the fibers or solid particles that determines its corrosive resisting power."

"Density is wilfully sacrificed for economy of construction in modern concrete work. Under some conditions this may be justified, but any concrete exposed to water or to the weather on an important structure should be of the densest material possible. Concrete wet enough to run in a chute with the angles of slope now generally used should never be exposed at a water's edge, especially if the water is corrosive to calcium carbonate and if the climate is cold enough to cause freezing. In most instances such wet mixed concrete will begin to disintegrate within 20 years, and frequently in less than 10 years.

"The examination of disintegrated concrete on a number of structures under such conditions has almost invariably shown a large percentage of voids—not that it was honey-combed, but

that there was an expansion of the cement fibers. This applies not only to construction in which good materials have been used but to that in which it is not exposed to sea water or sulfate waters. Such waters bring about conditions that even the best concrete may not withstand for more than a few years.

"It is believed that a void test and the inclusion of maximum limits would be desirable additions to the specifications for concrete on important exposed structures. It is realized that any addition of laboratory tests is not regarded with great favor in construction work; however, when present methods under the best of inspection do not always produce durable concrete, the small cost of such additional tests would be insignificant if they aided in producing better concrete. One procedure for making the tests that gives satisfactory results will be described."

"... Progress in making durable concrete has resulted from using good materials and exercising care in mixing and placing; yet with all these precautions many structures begin to disintegrate after a few years of exposure. Many of these structures become strong enough a few months after construction for the load they are to carry, and if this strength could be maintained they would remain safe. Structures disintegrate, even when the inspection has been good and every care has been exercised to see that good materials are used..."

"These conditions force the realization that present-day knowledge of concrete is still quite meager..."

"It seems that the most logical procedure is to examine existing structures. If the calcium solubility index at a depth of $\frac{1}{2}$ inch or more from the surface is low the concrete should be protected. It is believed that, when the safety point of alkalinity is exceeded, reliance should be placed only on some impervious surface coating, such as paint. After cracks have developed, protection is very difficult. Millions of dollars in future repairs and replacements probably could be saved by protecting exposed structures as they fall below the safety limit of calcium solubility. Many exposed structures apparently in good condition will be found to be below the safety limit, but it is likely that a gradual weakening is taking place and that

eventually this may cause failure."

In a discussion on a Symposium on the Behavior of Concrete, before the American Society of Testing Materials 1923, the following remarks were made:

Henry S. Spackman said: "... Portland cement as it is made to-day, though in the main a satisfactory material, is far from perfect. The durability of concrete is dependent not on the durability of the cement but on the protective action of the aggregate. This is evidenced by the fact that neat cement is never used in construction work. As used in construction, portland cement is purely and simply a binder or glue. As a binder it fails to give complete satisfaction because of the relatively slow reaction with water of some of its components. As a consequence, the strength of concrete is a question of weeks or months instead of hours or days and the final strength developed is always subject to variability, because of the impossibility of maintaining on the work, uniform conditions suitable to secure the best results over the period required for the cement to become completely hydrated. As a result, especially where the concrete is subject to rapid drying out, we may have a considerable percentage of partially hydrated or inert cement which not only gives no strength but may be a source of weakness at some future time through expansion caused by its delayed hydration should water come into contact with it."

R. W. Lesley, referring to plans for increasing the use of cement in this country, said:

"... At my suggestion, for the purpose of carrying out plans then made, Ira A. Shailer, a skilled and distinguished engineer and one of the contractors on the Croton aqueduct system, visited Paris to investigate from a technical standpoint the work done and the methods of construction. On his return to this country I consulted with him and advised him of the funds raised for the enterprise, but was surprised to have him say that he would have nothing to do in connection with the building of such work in this country, as he was convinced from his investigations that with American labor, American methods and American supervision he could not risk his reputation as an engineer in work of this kind. This was the conclusion of an important engineer, himself familiar with concrete

dams, aqueducts and other similar construction."

J. T. Campbell said:

"While our experience with concrete for exposed structures has in the main been very satisfactory, there have been several instances where concrete in service from seven to ten years has crumbled and disintegrated to such an extent as to endanger the structures and require extensive repairs, in some cases amounting to complete rebuilding."

"From our experience with disintegrated concrete we believe that any concrete that is not impervious to water will ultimately go to pieces, due to the fact that the water in going through the concrete dissolves out soluble portions of the cement causing crystallization to take place and expansion in the interior of the structure separating it into cleavage which allows more moisture to enter. During winter, alternate freezing and thawing will add to the disintegration and its progress will be greatly accelerated. We are attempting to make all our concrete structures as impervious as possible by using a combination of ingredients which will give the densest mixture; that is, a mixture with the least amount of voids. We cannot help but believe that the cement, which up to this time has never been suspected, has something to do with the disintegration in that chemical compounds form when the cement sets and the expansion and contraction which takes place when cement sets undoubtedly causes checks which allow the water to gain access to the structure; and when the path for water through the concrete is once opened up, the structure is doomed. The present tests for cement do not give us sufficient information concerning these characteristics of the material and unless further information is developed along these lines the writer believes that the only way to construct a job that will be absolutely safe is to use some form of hardener or surface finish which will absolutely close the pores of the concrete and prevent water gaining access, for our experience with concrete floors without such hardener has generally demonstrated that the floor will dust and become ragged and rough from usage in a short time, and that the surface thus presented is far from being impervious. In our recent designs we have endeavored to cover all con-

crete outside walls of structures with earth fill or brick veneer to give it protection against the rain and water, as we can never prophesy that the concrete, even though constructed with the best methods known to date, will not fall to pieces in the next seven to ten years."

Mr. P. H. Bates said, page 165, that somewhat more than 50 per cent of cement is soluble in water, and that "hydrated cement, the matrix of concrete, is just as soluble as limestone, in fact it is more soluble." He also said, page 161, "Are we not fundamentally wrong in saying or hoping that cement products should be even approximately permanent?" He further said, page 167, "Our present methods only very roughly approximately enable us to predict the suitability of a concrete for any particular use": and, page 169, "There is no question but that a deductive study of concrete forces us eventually to conclude that we are grossly ignorant of cement." And he suggests the modification of the slogan "Concrete for Permanence" into "Concrete for Study," page 171.

Mr. J. T. Collier said, page 244:

"I would also cite a case of a concrete bridge nearly a mile long that I was asked to inspect last fall. Although this bridge had been completed less than two years, it was in such bad condition that the concrete had fallen off the bottom of about one-fourth of the girders, and large areas of the slab. Why? Simply because the steel was so close together that no good concrete could get past it. Do not think this is a solitary case. I have seen numbers of them."

In Bulletin 126 of the University of Illinois 1921, it is said:

"Reinforced concrete does not appear likely to be a durable material in a place where a corrosive influence on steel, such as sea air, is active, unless proper protection against the formation of shrinkage cracks is made."

"It is suggested that the prevention of shrinkage stress in concrete might be accomplished in two ways, either by finding a cement giving less expansion and contraction, or by the use of a perfect waterproofing treatment."

Such a cement has not been found; and the waterproofing treatment would not prevent

shrinkage, which occurs in dry air.

That many concrete structures, which were at the time of their construction considered as perfect as they could be made, are disintegrating, is being reluctantly admitted. Anyone who will examine many of these structures will find abundant proof, and there have been many failures and collapses.

That disintegration is being admitted is shown by the titles of some of the papers that have been quoted.

Also, although the literature of concrete is so extensive that it would take a lifetime to read it all, it is admitted that our knowledge is as yet very meagre. Of a list of 9425 references on the subject, kept by the Lewis Institute, 1273 relate to "destructive agencies."

The American Railway Engineering Association published a Bulletin (211) in 1918 on "A Study of Concrete Failures."

The American Concrete Institute has a Committee on "Destructive Agents and Protective Treatment." One experienced engineer reporting to the Committee says: "Real high grade concrete is quite rare, and structures without some defects are rare."

The American Railway Bridge and Building Association has a Committee on "Methods of Repairing Disintegrated or Poor Concrete."

A Committee of the Detroit Engineering Society submitted a report November 2, 1925 and sent out a circular to users of concrete in which it is stated:

"The character of structural concrete now being obtained in this city is a matter which is causing grave concern to all who are thoroughly informed regarding local conditions.

"Tests made from a number of the large local construction projects have indicated that concrete, as being produced, is, in general, very deficient in strength as compared with the strength assumed in the design calculations. In recent tests made by the Department of Building, samples of concrete taken from local work showed in some cases about one-half of the strength which is assumed as a basis of the design of the structure."

The causes of defective concrete were classified, and recommendations made.

In a pamphlet by the Kansas City Testing Laboratory, on Cement and Concrete, July 1,

1925, reference is made to "widespread deterioration of concrete structures of all kinds."

An experienced engineer says: "I have personally examined many million dollars worth of bad concrete, some of which was undoubtedly caused by unsound aggregate."

Various reports and papers classify the causes of defective concrete and of failures. They may be stated as follows:

1. Poor cement.
2. Defective aggregate.
 - (a) Stone not durable (as in the Nashville bridge).
 - (b) Aggregate not clean.
 - (c) Presence of too much clay or organic matter.
3. Impure water.
4. Improper mixture.
 - (a) Poor grading of aggregate.
 - (b) Excess of water.
 - (c) Insufficient mixing.
5. Poor workmanship.
 - (a) Segregation.
 - (b) Inaccuracy in proportioning and in controlling the quantity of water.
 - (c) Carelessness in placing.
6. Improper curing.
7. Insufficient protection or heating in cold weather.
8. Removing forms too soon.
9. Poor design.
10. Shrinkage and expansion after set.
11. Corrosion of the metal.
12. Localized abnormal changes of temperature.
13. Action of alkalies or sea water, or trade wastes or sewage; or atmospheric fumes.

This is a long list, and there may be other causes.

Mr. R. S. Greenman¹ says that the reasons for poor concrete have been proportioned as follows: 90 per cent from poor workmanship, 8 per cent from poor aggregates, 2 per cent from poor cement. He says that fine aggregate needs very careful examination. He cites one case where concrete gave trouble because the water used came from a brook on which was a factory making medicines; another where the sand was sharp and well graded but had some

yellow coated grains; another where the crushed stone all came from the same quarry, but some came by rail and some by trolley, and the latter was handled in cars which had not been cleaned and had in them some small quantities of stone on the verge of disintegration.

When one scans this list and considers the character of the usual workman, he may be inclined to agree with Professor White, who says:¹ "*It (concrete) has latent possibilities of harm which no other major building material possesses. Its faults are, so far as we know, necessarily inherent in the material.*"

Frost may be a potent cause of disintegration. If there is no liquid water in the pores, it may be frozen without harm, but if there is liquid water, it will expand; but if a hair crack develops, water may enter and cause progressive disintegration. Even hair cracks must be prevented if disintegration is to be avoided when concrete is exposed in the open air in conditions where ice may form.

Corrosion of the steel has been a frequent source of trouble. It is said that concrete protects steel from corrosion. So it may, as long as it surrounds the steel. But when cracks develop, as contemplated by the accepted theory, water may gain access to the steel, which then cannot be protected. Especially if the water contains salts, the danger may be great. There are many papers dealing with the effect of soil alkali or salt waters on concrete. Bulletin 1314 of the Department of Agriculture gives 36 pages of references to articles especially relating to the deleterious effects of soil alkalies and other chemical agents; and while many engineers believe that concrete may be used safely in sea water, if rich and dense, there are many cases of failure in sea water, and there is much difference of opinion regarding the constitution of the best cement for this purpose. In Technical Paper 214 of the Bureau of Standards, it is stated that "the best quality of concrete will disintegrate when exposed to severe alkali attack." This may be accelerated by corrosion of the steel.

To resist alkalies, it is said that limestones, dolomites and sandstones must not be used as aggregates. Professor McKibben in Engineer-

1. Am. Soc. for Testing Materials, 1914.

1. The Fundamental Cause of the Disintegration of Concrete, "Concrete," May, 1925.

ing News-Record, Sept. 29, 1921 gives a list of 14 structures which he has observed showing corrosion of the steel and partial failure of the concrete generally due to salt.

Trade wastes, depending upon their character, may cause disintegration. Sewage may do the same, and many concrete sewers are showing poor results. For this reason, I prefer burnt clay products for drains and sewers.

Mr. C. A. Newhall, in the Contract Record, March 29, 1922, discusses the action of ground waters on cement sewer pipe. He says:

"One of the most dangerous uses to which cement is now put is in the construction of sewer pipe. These thin walled structures offer ideal conditions for the action of disintegrating agents.

"Any engineer that sanctions the use of cement sewer pipe and drain tile in the future is surely laying up certain trouble for himself . . ."

"Until a cement pipe can be made impervious to capillary percolation of water and long continued action of acid ground water, it would seem the wise theory for cement people to turn their products to a better use."

In using concrete in freezing weather it is not enough merely to keep the materials from freezing while being mixed and placed. Mr. P. J. Freeman, in the Proceedings of the American Society for Testing Materials for 1923 states that a \$300,000 reinforced concrete building was built the preceding winter and began to go to pieces when the first warm day came: and that it is doubtful if satisfactory repairs can be made to save it.

Mr. Newhall has also called attention to the disintegration of concrete in railway tunnels, due partly to the locomotive fumes, and partly to the solution and removal of the cement by percolation of water through an originally porous concrete. (See Proceedings of Northwestern Society of Engineers, Seattle, Oct.-Nov., 1916. See also Proceedings of the Am. Soc. for Testing Materials, 1923, Part II, p. 189).

There is a German book of 452 pages, by Kleinlogel, entitled "Einflüsse auf Beton," discussing the chemical, mechanical, and other effects of air, water, acids, oils, lyes, gases, earths, stored materials, etc., on cement mor-

tars, concrete, and reinforced concrete, and the means for diminishing and preventing such effects.

Also there is a recent German book by Dr. Richard Grün on "Der Beton," which was reviewed in part as follows by Mr. P. H. Bates in the Engineering News-Record, May 20, 1926:

"The third and main portion of the volume is all-inclusive and covers a most astonishing list of materials that may be and apparently have been harmful to concrete. One can find discussed the origin, general properties and the effects on concrete of many acids, bases, organic and inorganic salts, oils, fats, colloids, and a great variety of the commercial liquid commodities which might in their course of manufacture come into contact with concrete. Included among these liquids are certain ones of historical interest (in the United States) only, as beer and wine, and such an important one, at least in Germany, as sauerkraut, although it is surprising to find this classed as a liquid. The array of names of materials that have been the subject of investigation as a result of their attacking concrete is so imposing as to raise the doubt if concrete has any chance to endure even for a brief time, let alone be permanent.

"The final portion, given over to remedial measures that may be adopted, indicates that Germany is, like the United States, well supplied with almost countless integral and applied agencies which are suggested as the panacea for producing lasting, unattackable concrete . . ."

If concrete disintegrates, the defective material must be dug out and replaced. This may be done by the Cement Gun. The Cement Gun Company has repaired many concrete structures, and has placed gunite around many steel beams and girders. I am informed that tests have shown that steel I-beams encased in two inches of gunite show an increase of strength of at least 25 per cent. Disintegrated concrete may also be repaired by the methods used by the Western Waterproofing Company, replacing the defective concrete and covering with a coating of one of the few waterproofing compounds which have withstood tests, either alone or in combination with a rich mortar, and so making a waterproof surface. Officials of these two companies have told me that there is an

enormous amount of concrete disintegration.

It is important to study failures of concrete, in order to arrive at the cause, if possible. We must remember that we live in a world of law, and that everything that happens has a reason. We must seek the reason in order to learn the law, conform to it, and avoid mistakes in the future. But a reason is not an excuse.

I am fairly clear in my own mind as to what is necessary to obtain good concrete. First, it must be made as dense and as impervious as possible, especially at the surface. It will not be impervious at first, and it must be properly cured, in order to give to the colloid the necessary water to form a dense compound filling the pores. Curing is very important, and is often neglected. Then its moisture content must be kept as constant as possible. It is not possible to keep it constant. I am becoming convinced that it is desirable to give the surface of all concrete exposed to the weather a surface treatment with water-proofing material. It is most important to keep water from getting in or out. The pamphlet of the Kansas City Testing Laboratory on "Cement and Concrete" states:

"It is just as important that concrete be painted as that wood be painted. Wood is much more capable of withstanding alternate drying and wetting than concrete."

I am inclined to think that this is correct, and it conforms to the views of Professor White which have been quoted. Of course it adds to the expense of concrete. Finally, percolation of water through concrete must be prevented by efficient waterproofing unless, as in a dam, the surface is exposed to water all the time and becomes itself waterproof.

This will not always be the case, and in recent years we have the example of the Gem Lake dam, and the Manitou dam; and also the Gleno dam in Italy, which collapsed in 1923, causing about 500 deaths; and, more recently still, the Dolgarrog dam in North Wales, which failed in 1925.

Professor White states the conditions as follows:

"... The conditions which must surround concrete to enable it to attain strength and to maintain this strength are three:

"a. The materials must be of good quality,

properly proportioned, and mixed with a reasonable amount of water.

"b. The concrete must be kept wet long enough to enable the cement to react with enough water to give the needed strength.

"c. The moisture content of the concrete must be maintained at a reasonably constant figure throughout its whole life."

Considering the facts that have been presented, it would seem fair to draw the conclusion that it is *possible* to get a good original job, but there will still remain the stresses and cracks due to changes of moisture and the action of the loads, and the time effect, which defects are inherent in the material and preclude the possibility of predicting the life of a concrete structure.

Steel has other advantages over reinforced concrete, which should be mentioned; namely, the ease with which changes, additions, and repairs may be made: the possibility of removing a steel bridge to another place, or of removing a steel building easily if the land should be needed for another purpose, and the fact that steel has some salvage value. You cannot move a concrete bridge to another location. You can move a steel bridge, and many are so moved. A concrete building, once erected, is generally difficult to alter or remove. The Atlanta baseball stadium is said to have been built of steel because of the ease of removal in case the land should be needed for another purpose.¹ Also, steel allows more space in buildings, especially high buildings, because the columns may be smaller. In bridges, concrete columns have sometimes seriously restricted traffic, as I am told is the case in the Superior-Detroit High Level Bridge at Cleveland.

Consider now the question of economy. No doubt a great deal of good concrete has been made, and also a great deal of poor concrete. The inherent and fascinating ease and simplicity of the process of just mixing sand, gravel, cement and water and pouring it like mud into a form, has naturally and necessarily, under the pressure for economy, led many builders to use cheap labor and the materials that were most handy for the job. The tendency for economy and the characteristics of human nature still

1. The Harvard baseball stands were built of steel for this very reason, and have already been moved twice.

exist, and always will exist. It was a great step forward when it was recognized that the aggregates required just as close scrutiny as the cement; it was another step forward when it was recognized that the most careful proportioning, and expert supervision of field methods were equally necessary, and another when the importance of using as small a quantity of water as possible was discovered. I give great credit to the Portland Cement Association for the work that has been done at the Lewis Institute, and to Professor Abrams, who directs that work. I think, however, that concrete is frequently made too dry.

But one reason why concrete structures have in many cases been more economical than steel has been that the Building Laws have discriminated unfairly in favor of concrete and against steel. The enthusiasm for reinforced concrete has spread even to building commissions and legislatures.

For instance, the St. Louis code provides, for fireproof buildings:

"All exterior columns and all girders or other framing supporting more than one story of masonry shall be protected at every point by fireproof material at least 8" thick on their outer surfaces and at least 3" thick on their inner surfaces.

"All interior columns shall be protected at every point by fireproof material at least 2" thick.

"Floor and roof beams and other framing not supporting more than one story of masonry, shall be protected at every point by fireproof material at least 2" thick.

"Section 2299. The minimum covering of concrete over any portion of the reinforcing steel shall be as follows:

On flat slabs not less than 1"

For beams, girders, ribs, etc., not less than 1½"

For columns not less than 2".

All exterior steel columns must have 8 inches of concrete over their outer surfaces, while reinforced concrete columns need have only two inches of concrete outside the steel! What an unfair discrimination! Similar discrimination is found in the Building Codes of Buffalo, Denver, Philadelphia, New York, Chicago, Boston, and other cities.

If these unfair discriminations were removed, and if more care were exercised to get skilled labor, to select suitable materials, and to have expert supervision, there is no doubt that reinforced concrete would not work out to be more economical than steel, in many cases in which it does now work out to be more economical.

But what is the economy of a few dollars anyway, in the face of the other advantages of steel?

Notwithstanding all this, many have been and are carried away by enthusiasm for reinforced concrete. In the discussion before the American Society of Civil Engineers in 1902, one prominent concrete engineer, since deceased, who had patented a reinforcing bar, said:

"When properly built, this steel-concrete construction will not crack; will not be disintegrated by frost; will not be dissolved by the elements; and, in the speaker's opinion, is the only kind of engineering structure that can be considered permanent, with the exception of one or two kinds of rock masonry, the cost of which in most cases would be prohibitive."

When Professor White presented his paper before the Testing Association in 1911, one leading concrete expert said:

"... One cannot but be impressed by the somewhat startling results stated in this paper. If these statements were to be taken in a strict sense I am afraid we should all become desert-ers of concrete."

And he further thought that Professor White's results should not be accepted because based on tests of small specimens, regardless of the fact that many reinforced concrete structures are thin. Another concrete expert said:

"... In ordinary concrete structures made with a good dense mixture, I am of the opinion that no consideration whatever need be given to the swelling or shrinkage of concrete from moisture except during the initial hardening."

In Engineering News of April 4, 1912 is published an account of the meeting of the Am. Soc. for Testing Materials, held March 28, 29, in which the editor says:

"The report of the waterproofing committee brought about some excited discussion, during which several persons affirmed their belief in the imperishability of concrete and protested

against sanctioning any hint of any other possibility. The final outcome was that the progress report was sent back to the committee for revision. An interesting feature of the discussion was the statement that the committee is made up virtually of two groups: The impermeability men and the extraneous-waterproofing men; the implication was that the committee has a sort of cat-and-dog time in reaching any conclusions. Another item of interest was the statement by C. de Wyrall (Interborough Rapid Transit Co., New York City) that he has seen a thick concrete wall, originally made in best manner of 1:3:5 mixture, disintegrated to the degree that it was soft and rotten for a foot of thickness, over an area of many square feet, so that serious collapse would have occurred except for the fact that the wall carried no load. Mr. de Wyrall, who is a member of the committee, placed himself in the impermeability group, by the statement that his 9 years' experience indicates that extraneous waterproofing materials are very good materials provided water is kept away from them."

Professor H. J. M. Creighton in the *Journal of the Franklin Institute*, November 1917, says regarding this:

"... However, though 'it is no doubt true that many diseases can be cured by a practitioner who strenuously denies their existence and thus encourages the patient to resist and overcome them, it can hardly be expected that defective concrete walls or disintegrating piers can be strengthened by absent treatment, however vigorous be the denial of the injury or however prominent the denier.' It is much better to look facts in the face and attempt to find a remedy."

How much more reasonable than extreme enthusiasm is the sane attitude of Mr. F. C. Wight, the Editor of the *Engineering News-Record*, who said (*Am. Soc. for Testing Materials* 1923, p. 157).

"It (concrete) is, however, a complex material most susceptible to variation in the constituents and the process and subjected to a variety of service conditions. . . the over-emphasis of strength as the main requirement to meet service conditions may have resulted in a one-sided view of the material.

"... In our interest in the test we are in

danger of losing sight of the end for which the test is planned. We are failing to record the behavior of the actual structure and to tie up such behavior both to the tests and to the facts that these tests indicate.

"... Concrete is an obscure compound, the chemical nature of which is debatable, and whose reactions are neither understood nor measurable. Nevertheless, these reactions take place and their occurrence continues over an unknown length of time. It is not beyond the possibility of belief, for instance, that there is some truth in the claim that there is a critical age in concrete—a period somewhere between ten and fifteen years, maybe more, maybe less—when there occurs a subtle change in its nature. At any rate, changes in placed concrete do occur.

"... The inductive tests and studies have led to a number of theories and principles of the manufacture and placing of concrete, the best of which are embodied in modern practice. It is firmly believed that adherence to these principles will result in a stronger and more lasting concrete, but unfortunately only time can tell whether this is a fact, always assuming that there is no readily discoverable dead line in quality, above which concrete will be everlasting and below which it will be of the most temporary nature . . .

"Only those blinded by prejudice can fail to admit that a great deal of existing concrete falls far short of the expectations of its designers in appearance and in structure. Most of this concrete was satisfactory when the forms were first removed. It is probable that the builders when they left the job were convinced that they had turned over to the owner a structure that would continue in the acceptable condition they left it. For some reason or other there has been change with the passing of time—not change due to unexpected or undue load or wear, but change due to the natural exposure of the elements and the natural reactions in the concrete itself. To conceal such examples is to play the ostrich. They are usually where he who runs may read and as unexplained horrible examples they merely serve to deter the uninformed owner or prospective owner from accepting concrete as a suitable building material. Studied, however, and subjected to the light of criticism,

they may reveal basic errors which can be avoided in future."

Reinforced concrete is a comparatively new material. Though used and patented 70 years ago, it has only been in common use for about twenty-five or thirty years. Looked upon as a material that could be cast or poured around steel rods, with cheap labor, it appealed to the imagination, and it is not strange that it was adopted with enthusiasm, and that many engineers, experimenters, and teachers hastened to investigate and use this new material. Of course, those who had cement to sell were enthusiastic about it.

Let me say a word here about enthusiasm. What is enthusiasm? Did you ever stop to analyze it? I lately found a definition of it, by an English clergyman, which seems to me to be exact. He said: "Enthusiasm is a state of mind in which the imagination has got the better of the judgment." Analyze it, and I think you will see that this is precisely what enthusiasm is. If so, we must distrust it. I am aware that this is not the usual conception of the word, and that Emerson said that nothing great is ever accomplished without enthusiasm. But we all misuse words at times, and I think Emerson misused the word. Consider. Enthusiasm is not energy, nor persistence, nor reasoned conviction. It is a state of mind; and I think Emerson meant that nothing great is ever accomplished without a combination of energy, determination, persistence, and conviction. Enthusiasm is froth. When I see a man enthusiastic, I doubt his judgment. When I find myself growing enthusiastic, I doubt myself, and feel sure that I am being led by feeling and not by reason. Therefore, I say, always doubt enthusiasm and get your feet on the ground. Too many people have been enthusiastic about concrete. They have lost their vision.

Let me say that my views on this subject are not the result of inexperience with concrete. While I was a member and Chairman of the Boston Transit Commission, which constructed all the subways and tunnels in Boston, and the Charlestown bridge, we used many thousands of yards of concrete where it was considered suitable, and I have had considerable other experience with concrete. Some of the results have been good, others not so good.

I have no intention of condemning anything or anybody, but merely to state facts, and the conclusions that I think are properly to be drawn from them.

I have in the foregoing attempted to give the reasons for my confession of faith, which is as follows:¹

I would rather use burnt clay products than concrete for many purposes, as for roofing tiles and for drains or sewers, and in many cases for walls and as hollow blocks for floors.

For a structure which can be made of steel so as to be accessible for inspection and painting, I would much prefer steel to reinforced concrete. This includes railway and highway bridges, tanks and stand-pipes, stadia and grandstands, ships and barges, cars, etc.

How is it about structures like buildings, in which, if of steel, the metal is not everywhere accessible? Well, in such a case it is undeniable that steel is just as accessible as the reinforced rods in reinforced concrete; in fact, more so. Therefore, I would prefer steel for buildings. I would much rather have a steel frame building than a concrete building, especially if subject to earthquakes or hurricanes. Professor Alvarez of the University of California in a report on the Santa Barbara earthquake, published by the Portland Cement Association (for which all credit) says:

"The well riveted and strong but flexibly braced structural steel frame, fireproofed with good concrete properly held in place, is the safest frame of all. A frame of this character has never collapsed in an earthquake."

I entirely endorse this, and it did not need an earthquake to prove it.

I would rather have a steel column than a reinforced concrete column; a steel girder, protected by concrete or gunite, or haunched in concrete, than a reinforced concrete girder. I would rather have a column footing of steel beams than of reinforced concrete.

I would put my reliance in every case on the steel, which I can test and examine in its finished state before using, and which does not change its constitution after using.

1. In referring to this paper of Professor Swain, Engineering News-Record (November 4, 1926, page 740) said: "He did not indicate the particular uses, however, in which he considers concrete more suitable, or those in which steel is superior."

I believe that a steel arch may be made just as beautiful as a concrete arch: and, anyway, what is beauty compared to reliability and security?

When using steel I would be careful to have good inspection, careful workmanship, and I would design it so that the stresses should be as nearly determinate as practicable. I would use pin connections more than they are now used, and in designing riveted connections I would take care to make the distribution of stress as uniform as practicable. I would, of course, expect to keep the structure thoroughly painted, and I would design it so that this could be done. If the steel is inaccessible, I would take every precaution to prevent oxidation, and I could do this just as well with structural steel as with reinforcing steel, or even better, because in using reinforced concrete I am assuming that the concrete will crack.

I am told that in the case of the interstate bridge between South Carolina and Georgia, \$49,000 more was paid for a concrete bridge than a steel bridge would have cost. I consider this a wicked waste of the people's money. I would reverse the process, and pay more for

the steel bridge. I am also told that in a large city a concrete bridge is proposed, which will cost \$2,800,000 more than a steel bridge would cost. The annual interest on this at 5 per cent would be \$140,000, which would probably suffice to keep a gang of painters at work continuously. Could there be a more wicked or almost criminal waste of the people's money than this?

Notwithstanding, even if my judgment is correct, there still remains a multitude of other uses for concrete and reinforced concrete, as for foundations, mass work in general, walls and abutments, piers or their backing, dams, subways, roads, etc. The Portland Cement Association, in their Editor's Reference Book on Cement and Concrete, 1925 edition, enumerates 320 uses for concrete. I would eliminate 25 or 30 of these.

Why not use each material where it is most suitable and reliable?

I therefore give to you fabricators of steel the slogan:

Steel for Strength and Security, and you may add Reliability.

